Enabling cosmology with kSZ using FRBs

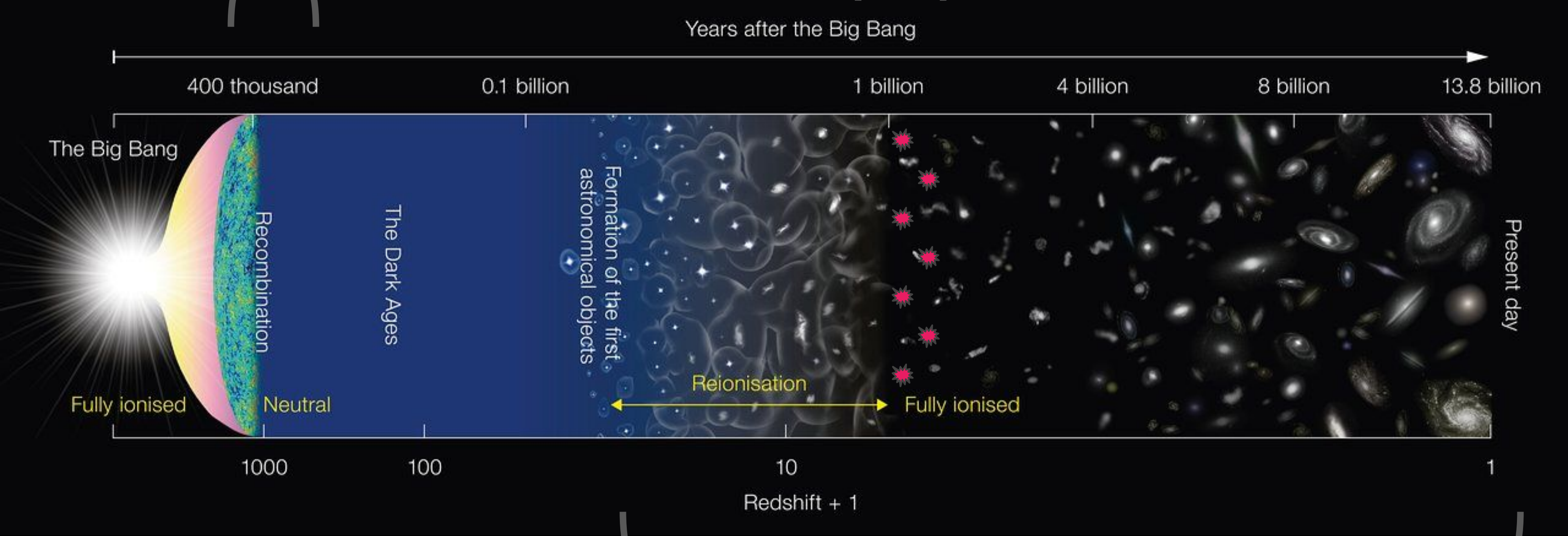
Mathew Madhavacheril
Perimeter

May 2021

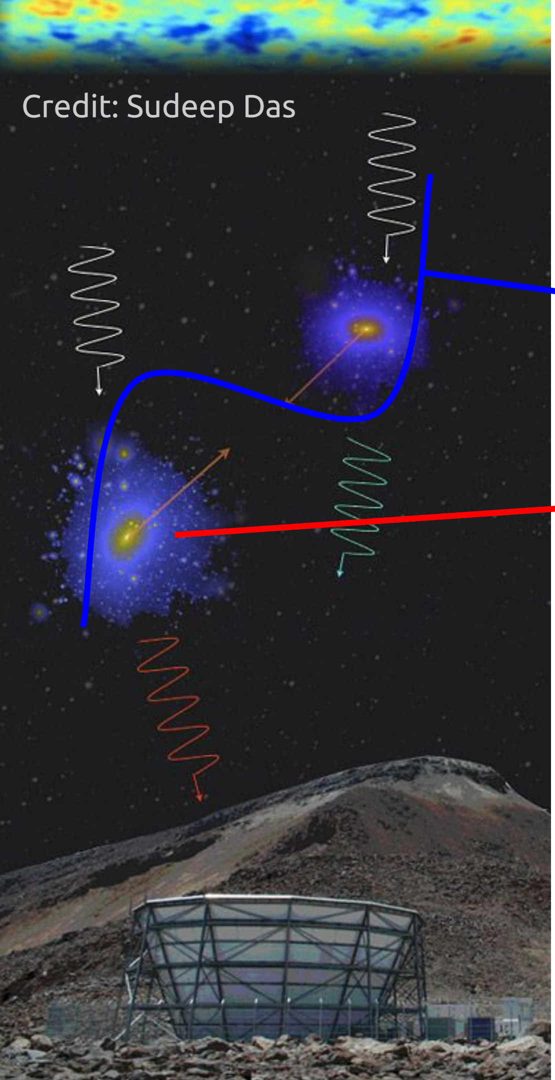
arXiv:1810.13423
arXiv:1901.02418

CMB backlight

FRB backlight?



Lots of (moving) free electrons

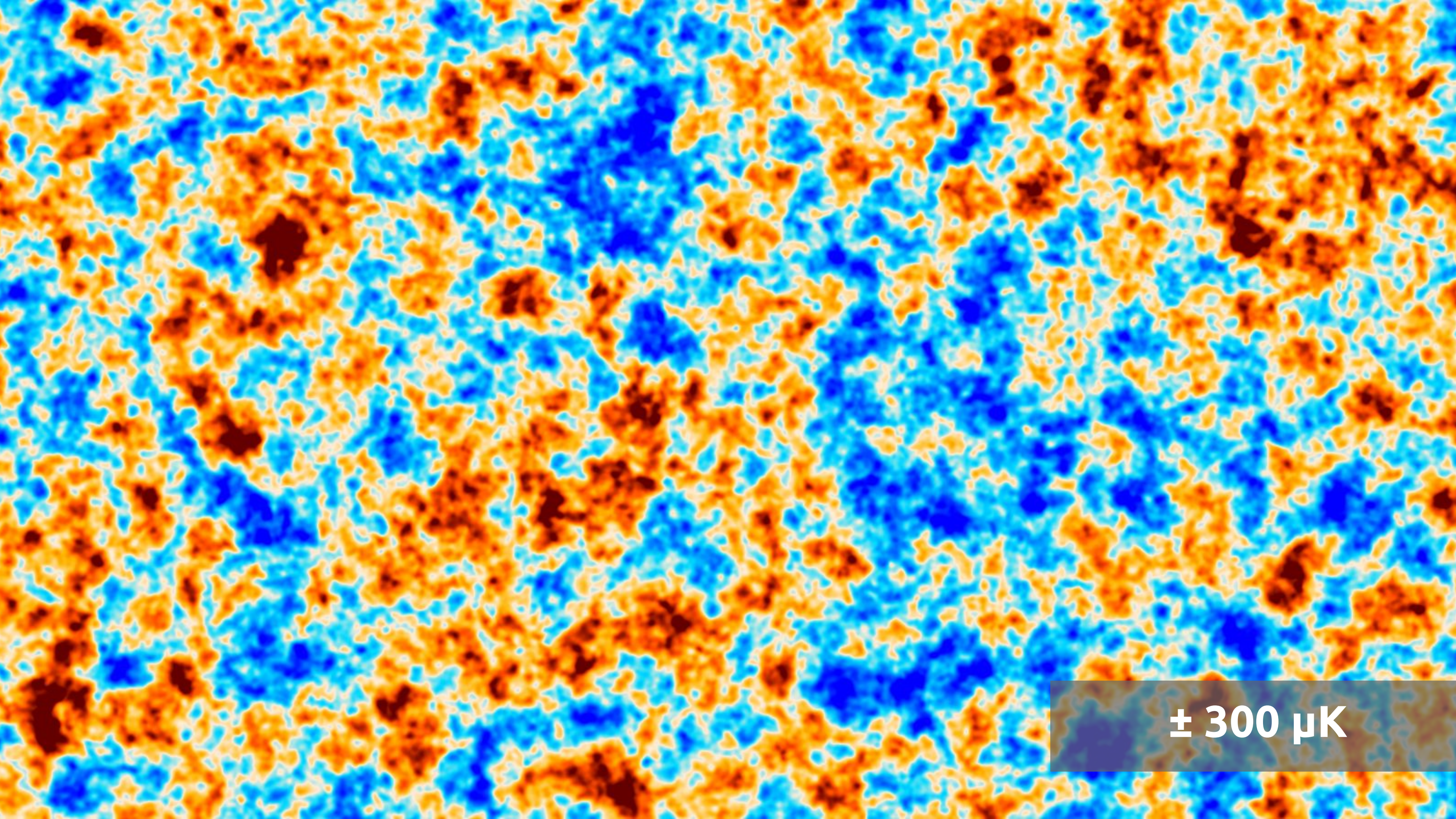


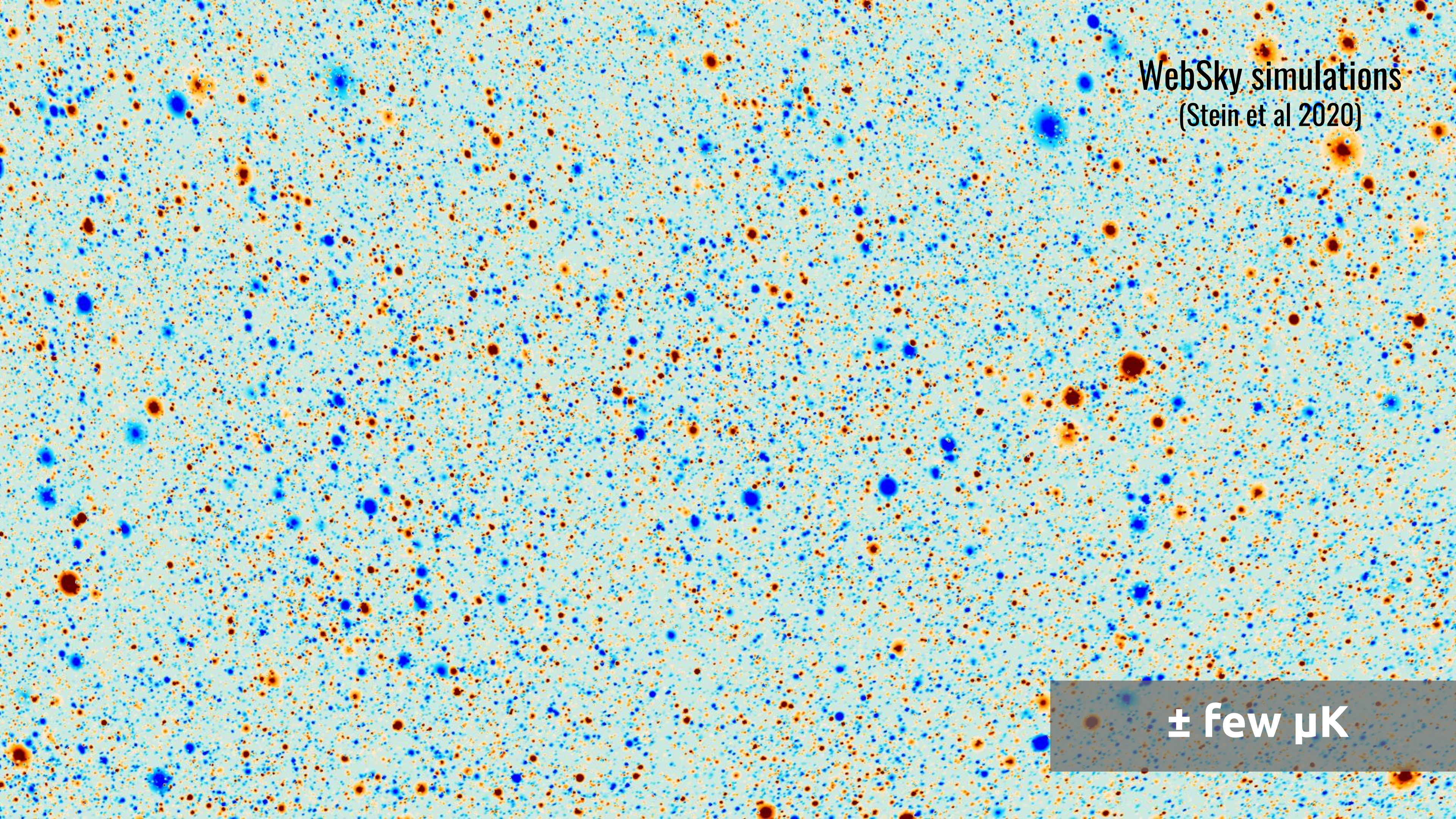
kSZ: Doppler shift of CMB photons scattering off electrons with bulk velocity

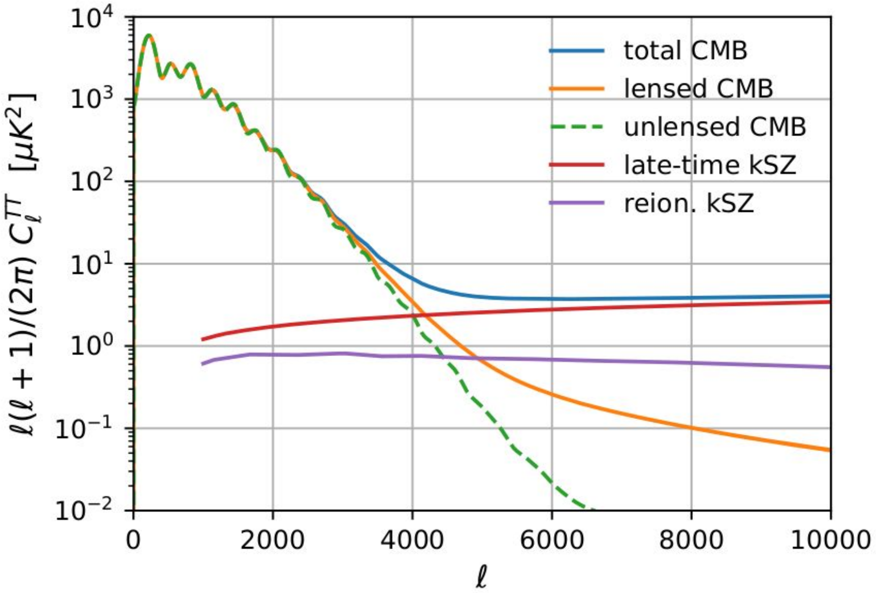
$$\frac{\Delta T_{\mathrm{kSZ}}(\vec{\mathbf{n}})}{T_{\mathrm{CMB}}} \sim \int d\chi e^{-\tau(z)} v_r \delta_e(\vec{\mathbf{n}}, \chi)$$

Contributions from

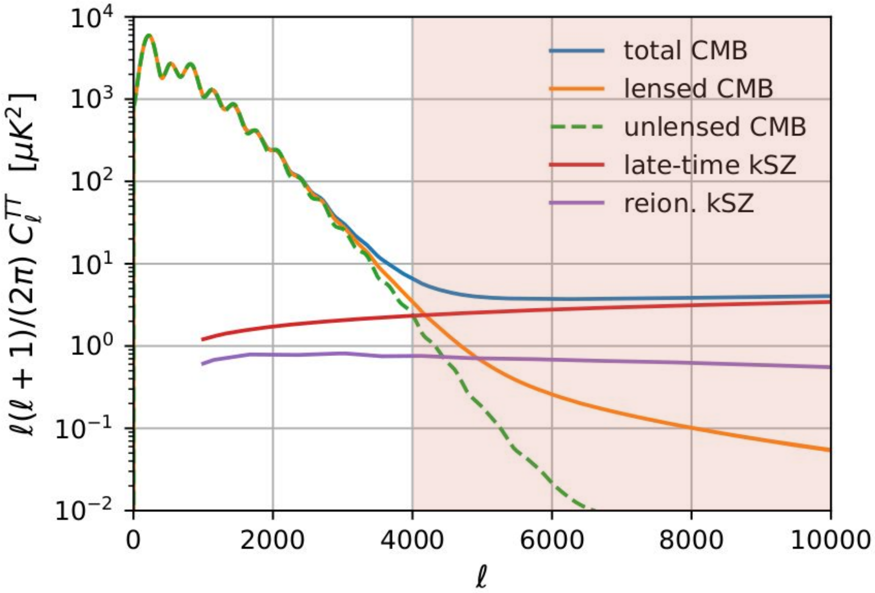
1. Reionization (from first stars) $6 < z < 20$
2. **Ionized gas in and between clusters $0 < z < 6$**


± 300 µK


WebSky simulations
(Stein et al 2020)
± few μK



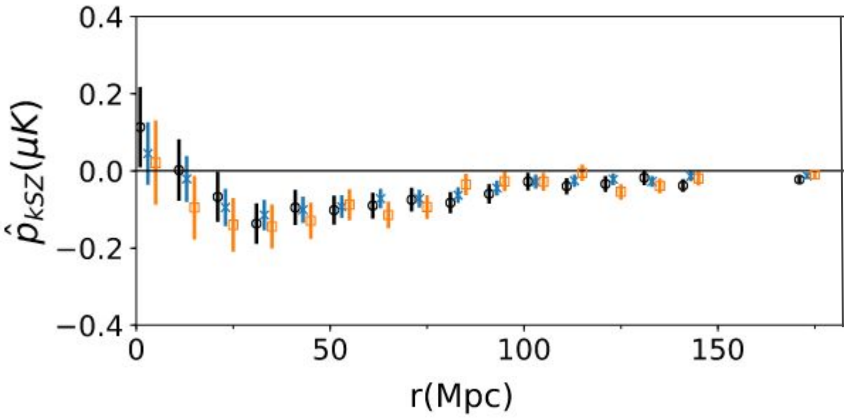
kSZ dominates CMB at ℓ>4000



kSZ dominates CMB at ℓ>4000

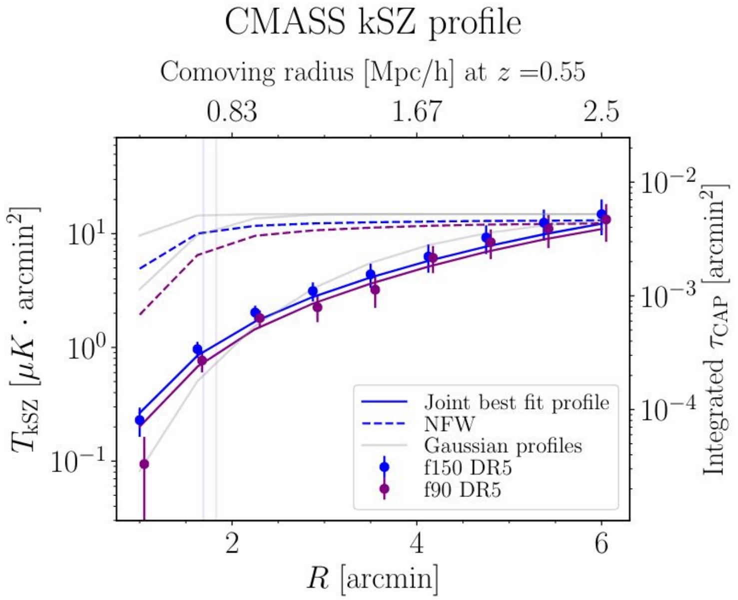
Modes to be explored by Advanced ACT, SPT-3G, Simons Observatory, CMB-S4

ACT x BOSS, Hand++ ‘12,
Calafut++ ‘21



Also:
ACT x redMaPPer, de Bernardis++ ‘16
SPT x DES, Soergel++ ‘16
Planck x SDSS, ‘15

ACT x BOSS, Schaan++ ‘15,
Schaan++ ‘20, Amodeo++ ‘20



See also: Planck x WISE, Hill++ ‘16

Currently detected only at the <**10 sigma** level
But expected to improve quickly with (deeper) CMB x galaxy overlap!
SNR O(100-1000) expected!

What can we learn with the kSZ effect?

$$\frac{\Delta T_{\mathrm{kSZ}}(\boldsymbol{n})}{T_{\mathrm{CMB}}} \sim \int d\chi e^{-\tau(z)} \delta_e(\boldsymbol{n}, \chi) v_r$$

Reionization
(Smith+ ‘17, Ferraro+ ‘18)

Missing baryons
(Lim+ ‘17, Hernández-Monteagudo+ ‘15)

Halo energetics and feedback
(Battaglia+ ‘18)

Astrophysics

Large scale anomalies?
(e.g. Terrana+ ‘16)

Growth of structure?
- Growth rate?
  (e.g. Alonso+ ‘16)
  - Neutrino mass?
    (Mueller+ ‘14)
  - Dark energy?
    (Mueller+ ‘13)

+++ ...?

Cosmology?

What cosmology can kSZ potentially constrain?

$$\frac{\Delta T_{\mathrm{kSZ}}(\boldsymbol{n})}{T_{\mathrm{CMB}}} \sim \int d\chi e^{-\tau(z)} \delta_e(\boldsymbol{n}, \chi) v_r$$

- **Unbiased density modes** inferred from velocities

$$v \approx \frac{faH}{k} \delta_m$$

- Velocities respond to **growth rate f** -> neutrino mass, dark energy, modified gravity

E.g Mueller+ '14
Alonso+ '16

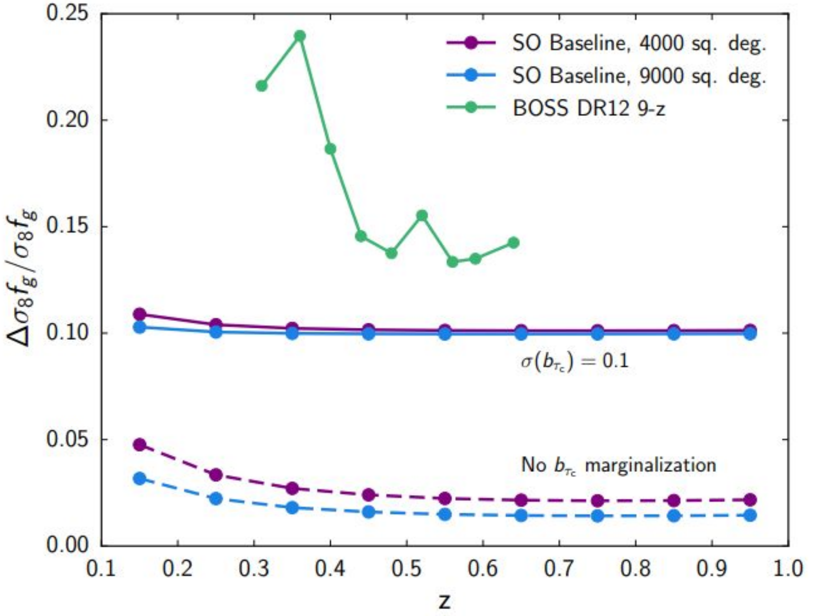
Astrophysics complicates this a bit

- Notorious "cluster optical depth"
- A catch-all term that includes our uncertainty about
  - Number density of electrons in halos associated with galaxies
  - Shape of the electron profile

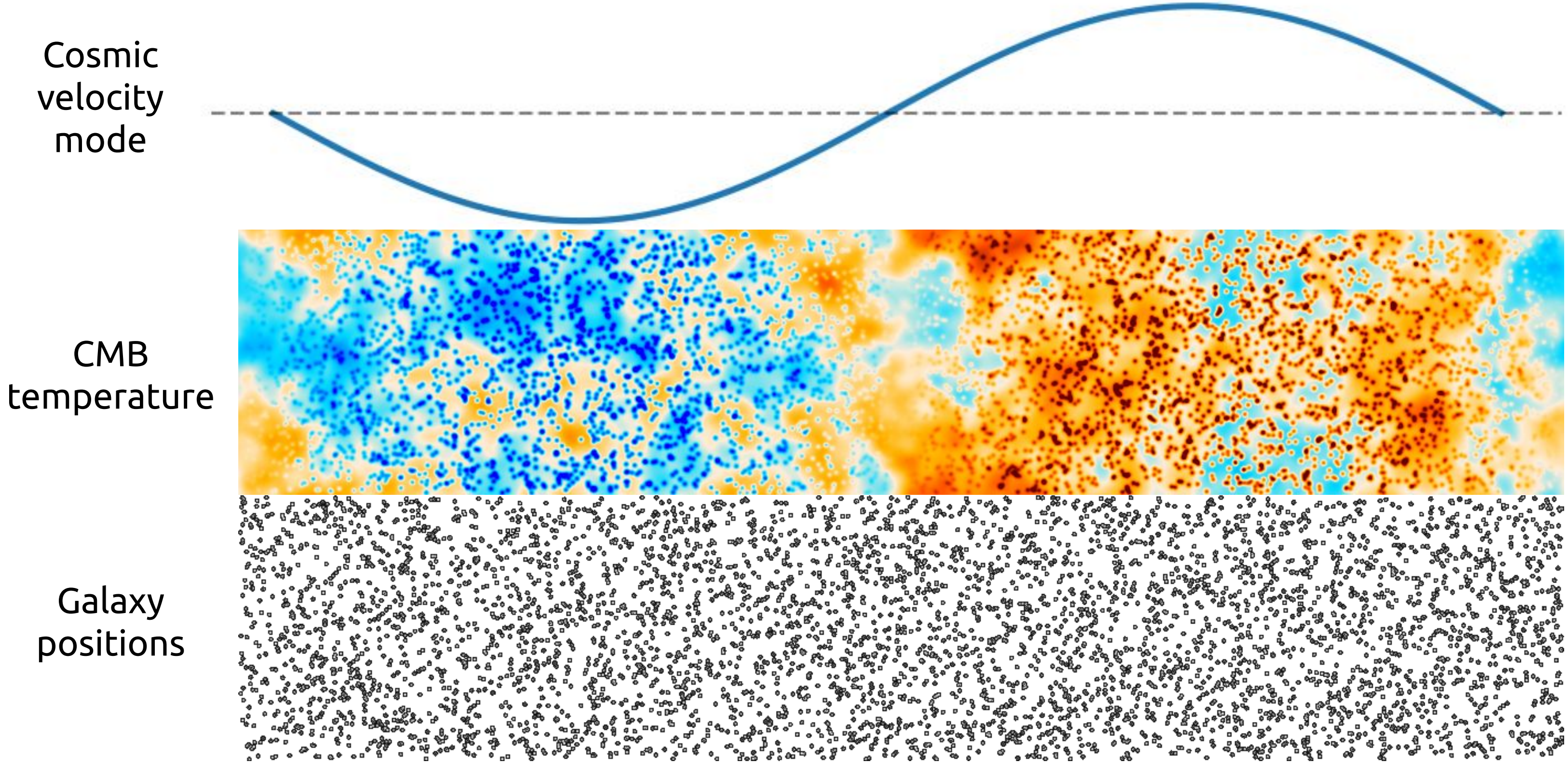
$$\frac{\Delta T_{\rm kSZ}(\boldsymbol{n})}{T_{\rm CMB}} \sim \int d\chi e^{-\tau(z)} \delta_e(\boldsymbol{n},\chi) v_r$$

But I'll show that this does **not** make it impossible to do interesting cosmology with kSZ!

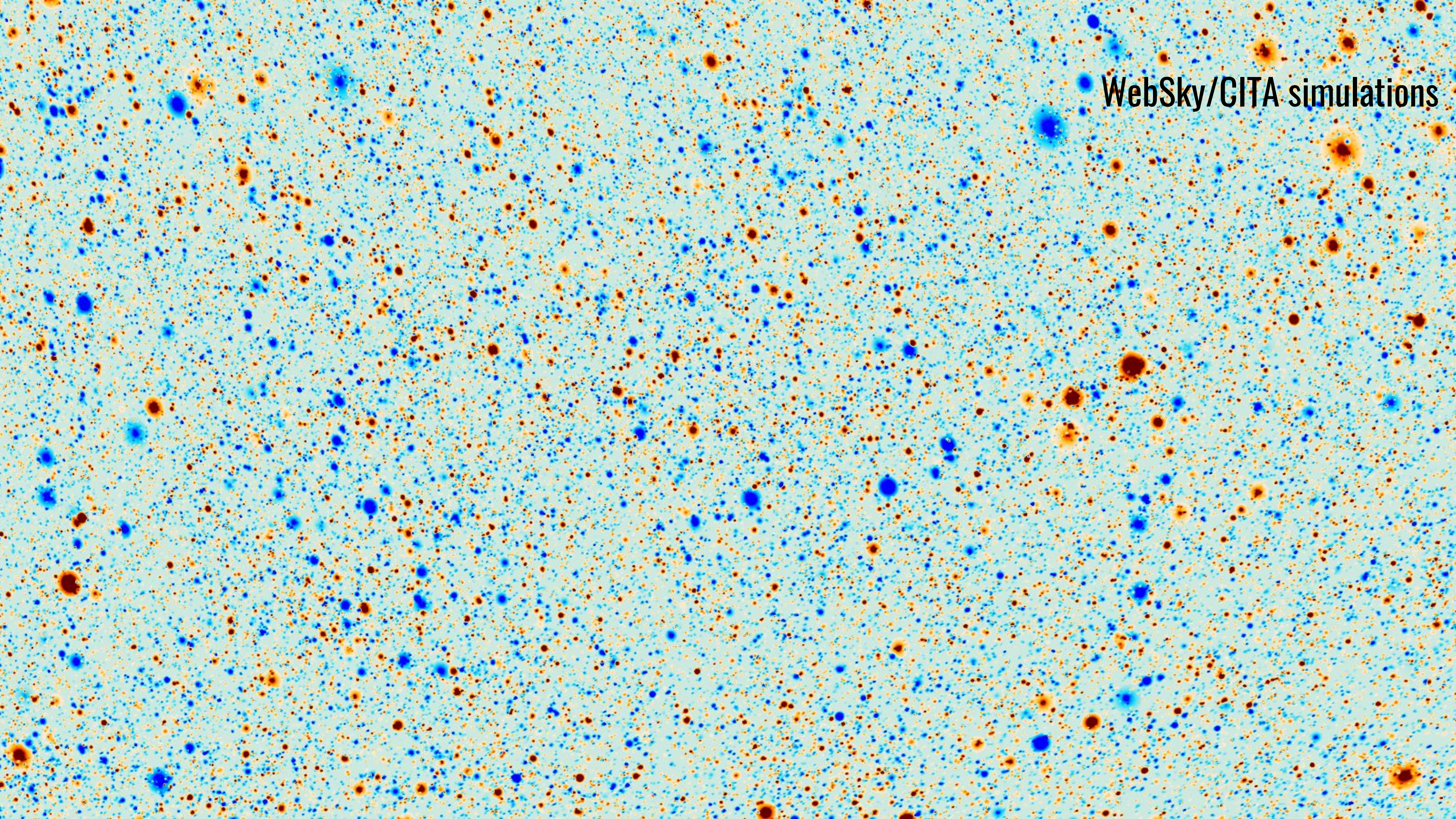
arXiv:1808.07445 SO Collab. produced by **Victoria Calafut**



Squeezed bispectrum cartoon: **kSZ**



Velocities from modulation of late-time kSZ cross-power with galaxies


WebSky/CITA simulations

Velocity Reconstruction Framework

- Average over quadratic pairs of modes -- effectively look for modulation of galaxy x CMB temperature power

$$T_{\rm kSZ} \sim \delta_e v$$

$$\begin{aligned}\hat{v}_{\rm rec}(k_L) &\sim \langle \delta_g T \rangle_{k_S} \\ &\sim \langle \delta_g(k_S)[\delta_e(k_S)v(k_L)] \rangle_{k_S} \\ &\sim \langle \delta_g(k_S)\delta_e(k_S) \rangle_{k_S} v(k_L) \\ &\sim \underbrace{v(k_L)}_{\text{Cosmology}} \int \underbrace{dk_S w(k_S) P_{ge}(k_S)}_{\text{Astrophysics}}\end{aligned}$$

Cosmology

Astrophysics

Scale-independent number $\mathbf{b_v}$

After velocity reconstruction, we have two probes of matter density

$$v = \frac{b_v f a H}{k} \delta_m$$

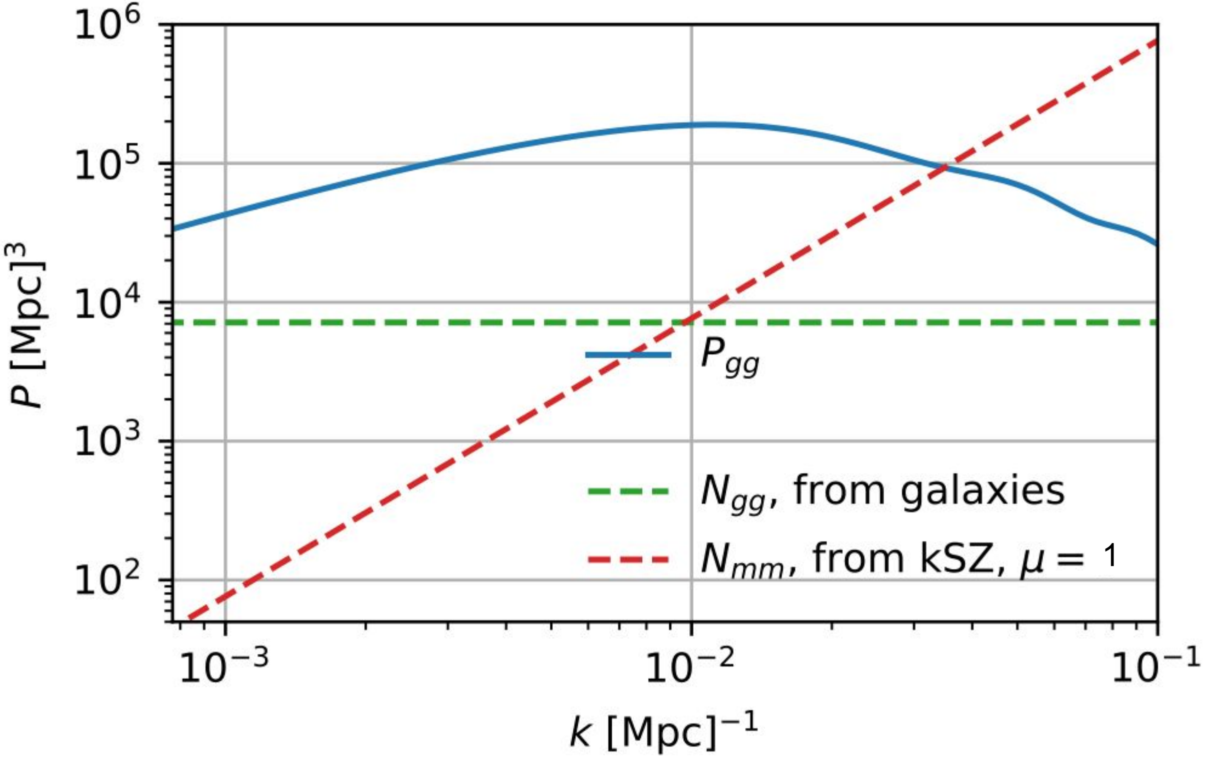
With some reconstruction noise

$$\delta_g = b_g \delta_m$$

With some shot noise

How does the noise compare between velocities and galaxies?
Squeezed limit noise is white
Convert noise on velocity to noise on matter density with k^2

Smith, **MM**++ arxiv:1810.13423



$$\delta_g = b_g \delta_m$$

$$v = \frac{faH}{k}\delta_m$$

kSZ Velocities outperform galaxy clustering at large scales!

Recap

kSZ tomography measures the largest scale density modes

Up to an unknown scale-independent normalization ("tau") that depends on $P_{ge}(k_S)$

With much lower noise than galaxy surveys!

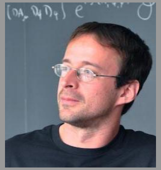
Both galaxy and velocity surveys are signal dominated and
hence sample variance limited on large scales:
This allows 2-3x improvement on fNL (local primordial non-Gaussianity) *despite unknown optical depth*
Munchmeyer, MM + 2018

Growth rate amplitude? (f)

MM++ 2019 arXiv:1901.02418

Nick
Battaglia

Kendrick
Smith



Jon
Sievers

What about the amplitude of the growth rate f ?

f(k,z) constrains neutrino mass, dark energy, modified gravity

Amplitude f(z) is degenerate with “optical depth” amplitude

$$v = \frac{b_v f a H}{k} \delta_m$$

$$b_v \sim \int dk_S w(k_S) P_{ge}(k_S)$$

Breaking this degeneracy requires an external measurement of **Pge**

Breaking tau degeneracy requires predicting Pge

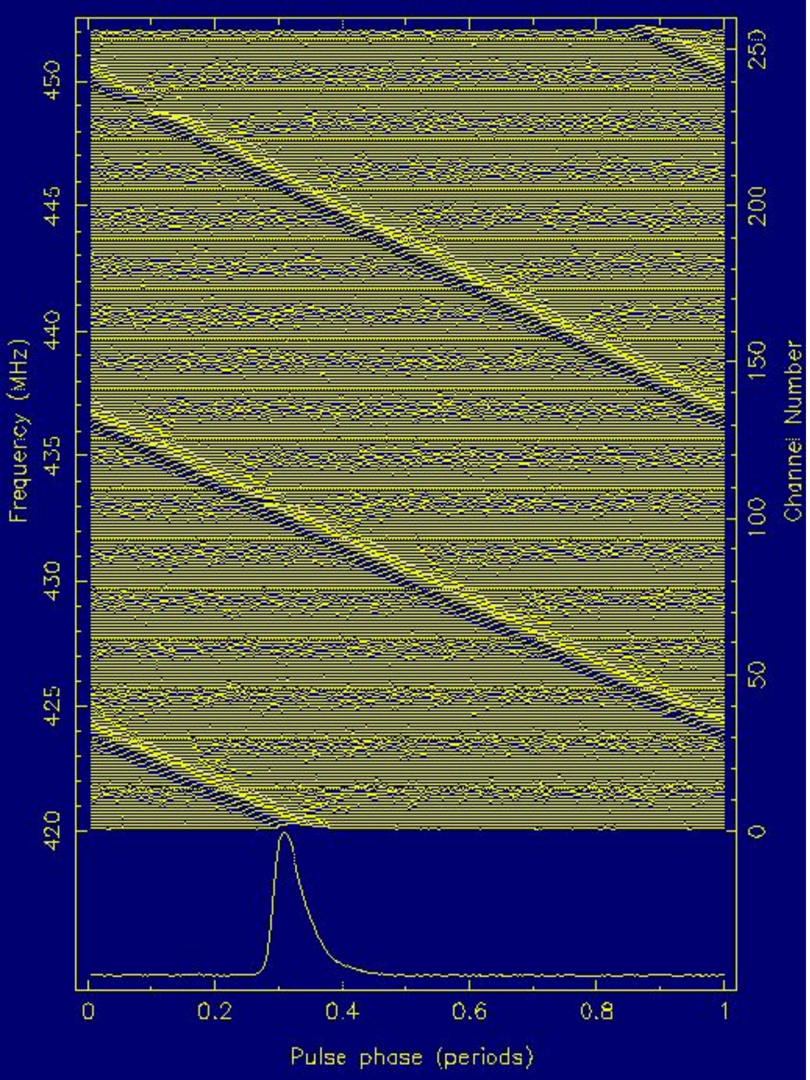
A data driven approach is to look for other effects that depend on **free electron density** and cross-correlate with the kSZ galaxy sample

Breaking tau degeneracy requires predicting Pge

A data driven approach is to look for other effects that depend on **free electron density** and cross-correlate with the kSZ galaxy sample

Possibility:

Dispersion measures of Fast Radio Bursts (FRBs)



Radio waves from energetic sources interact with intervening ionized matter and undergo dispersion

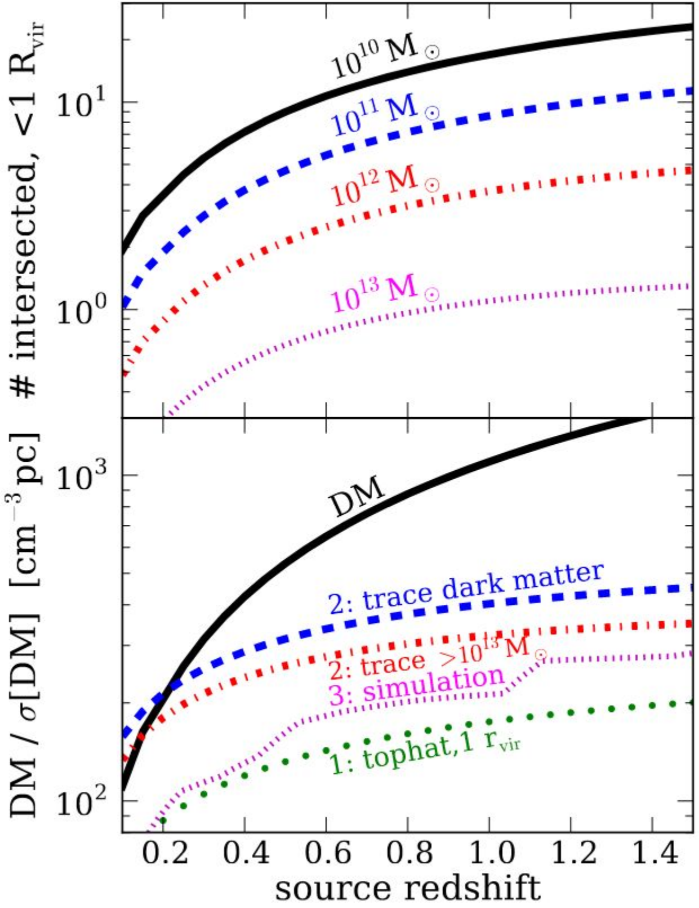
$$\Delta t \sim \frac{\mathrm{DM}}{\nu^2}$$

Higher frequencies push past free electrons and arrive earlier

Potentially **large number** of energetic sources at cosmological distances - **FRBs**

CHIME is seeing lots (see Kendrick's talk)

Matthew McQuinn 2013



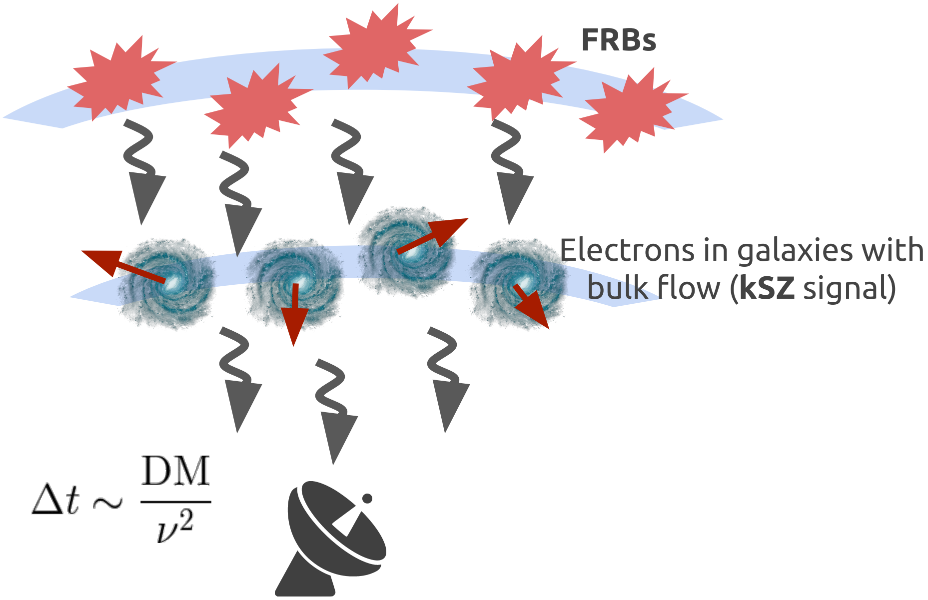
$$D(\hat{\mathbf{n}}) = n_{e0} \int_0^{\chi_f} d\chi \,(1+z)(1+\delta_e(\hat{\mathbf{n}}, z))$$

- DM has contributions from source/host, intervening plasma and Milky Way
- We are interested in DM anisotropies due to free electrons in and around haos
- Probes otherwise shy “missing baryons”

Breaking tau with FRBs

MM, Battaglia, Smith, Sievers arxiv:1901.02418

- FRB frequency-dependence of time delay depends on intervening electron density
- One contribution is electrons in galaxies whose "optical depth" we want to measure (apart from host galaxy and Milky Way)



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Breaking tau with FRBs

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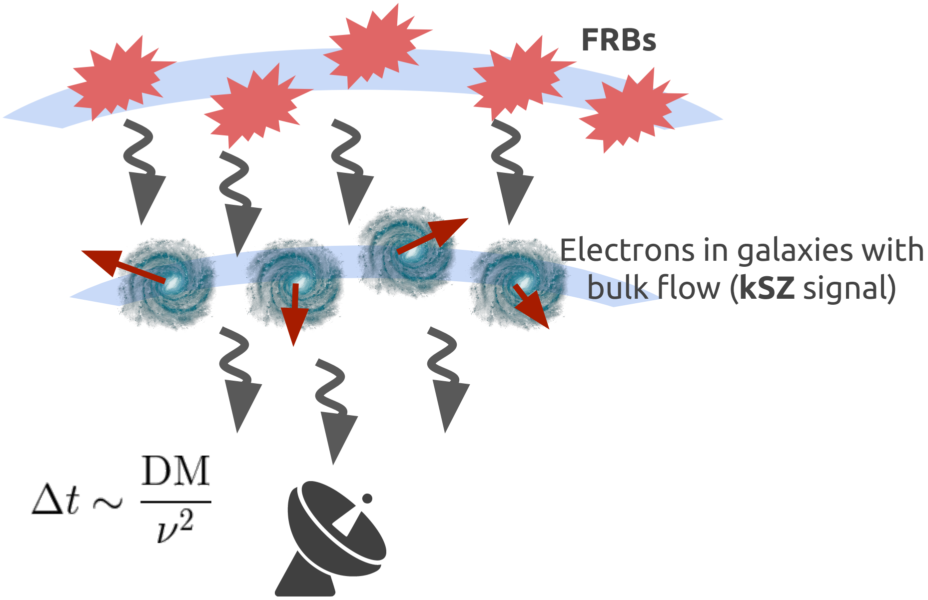
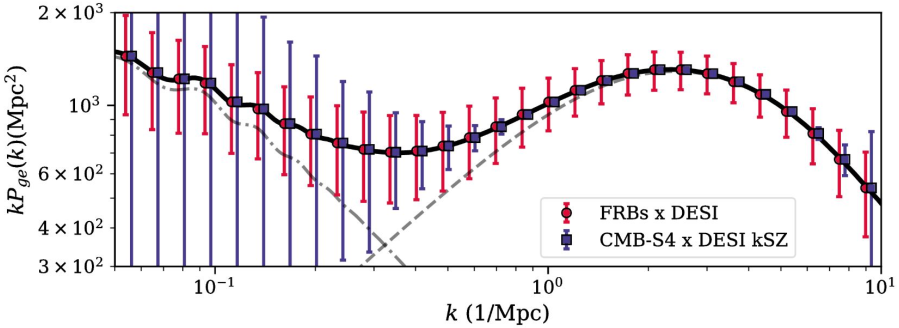
- FRB frequency-dependence of time delay depends on intervening electron density
- One contribution is electrons in galaxies whose "optical depth" we want to measure (apart from host galaxy and Milky Way)
- Cross-correlate DMs with galaxies used in kSZ estimator



$$\Delta t \sim \frac{\mathrm{DM}}{\nu^2}$$

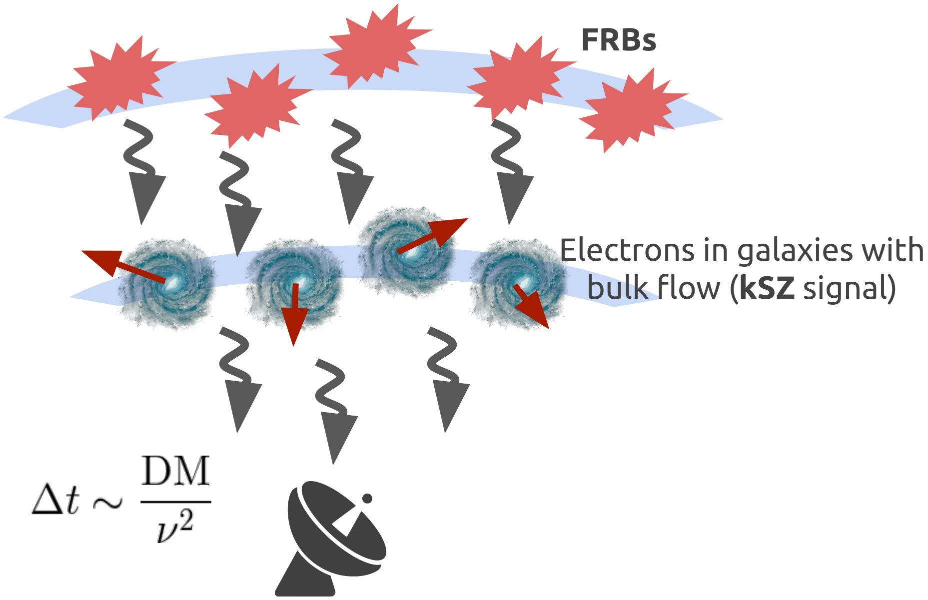
$$D(\hat{\mathbf{n}}) = n_{e0} \int_0^{\chi_f} d\chi \, (1+z)(1+\delta_e(\hat{\mathbf{n}}, z))$$

$$\mathrm{DM}(\vec{\mathbf{n}}) \times \delta_g(\vec{\mathbf{n}}) \sim P_{ge}(k_S)$$



See *Alonso 2021* for recent updates to cosmological DM theory

Breaking tau with FRBs



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$$D(\hat{\mathbf{n}}) = n_{e0} \int_0^{\chi_f} d\chi \, (1+z)(1+\delta_e(\hat{\mathbf{n}}, z))$$

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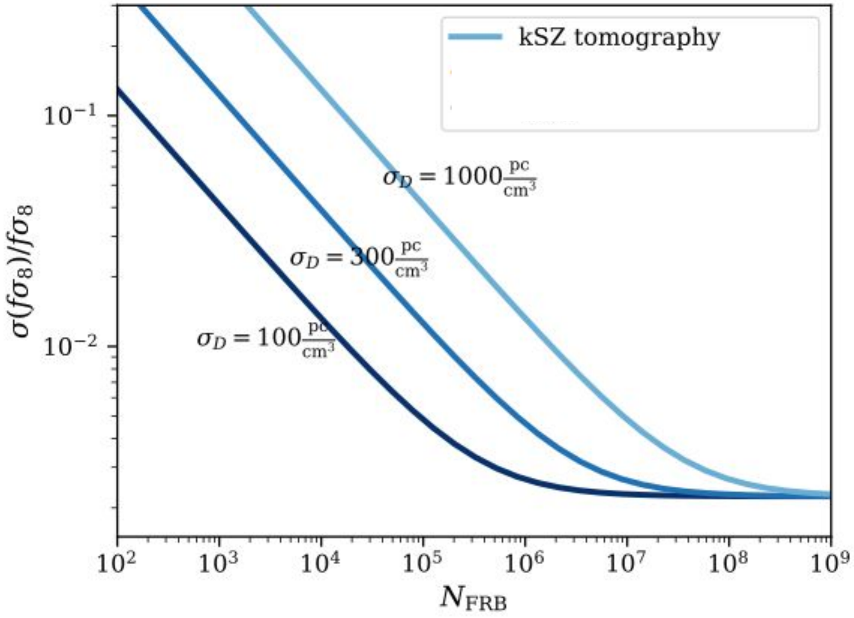


MM, Battaglia, Smith, Sievers arxiv:1901.02418

See *Alonso 2021* for recent updates to cosmological DM theory

Outlook

- Needs >1000 FRBs to do interesting science (number depends on scatter of DMs)
- Some redshift information needed, localization capabilities in radio instruments + follow-up and/or cross-correlations

  e.g. Masoud Rafiei-Ravandi, Smith, Masui 2019
- Source clustering can affect DM x galaxy cross-correlation, but likely negligible

  Alonso 2021
- Future experiments e.g. HIRAX, SKA-MID could find O(10-100) per day -> catalogs of 10^{5-6} not unrealistic! **(Maybe more in Kendrick's talk?)**

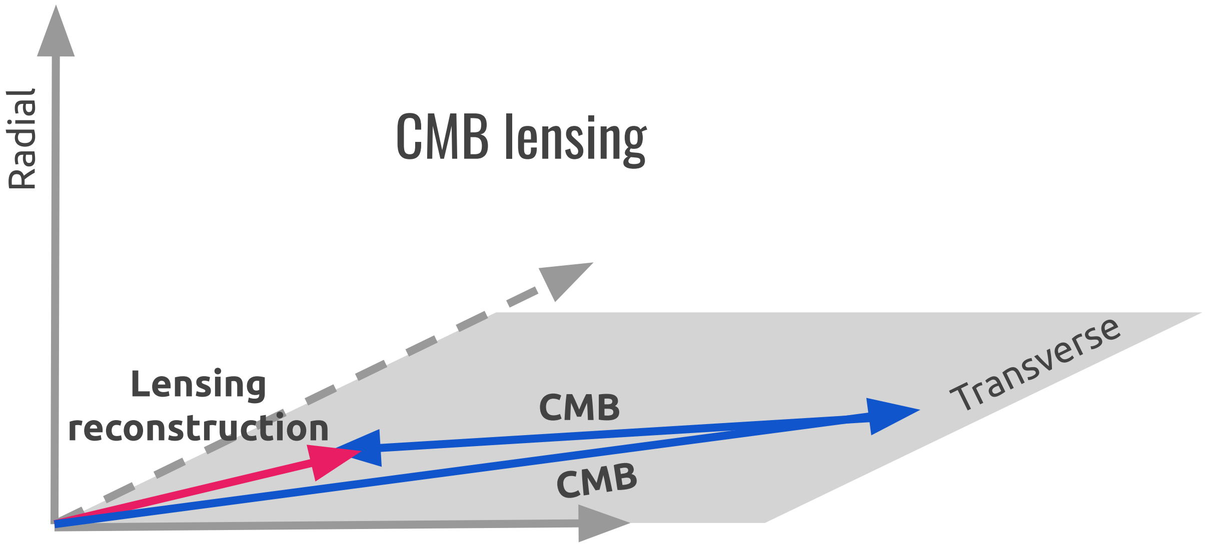
Conclusion

- Optical depth (tau) factors out as **scale-independent** uncertain amplitude
- kSZ velocity reconstruction does better than clustering at large scales
- Cosmological applications *(despite tau degeneracy)*
  - Improves non-Gaussianity sigma(fnl) through **scale-dependent bias** by 3x for CMB-S4 + LSST probing multi-field inflation, possibly other scale-dependent effects, e.g. dark energy perturbations
  - **Amplitude of growth** rate is perfectly degenerate with tau, but degeneracy can potentially be broken with localized **FRB** dispersion measures

Thank you!

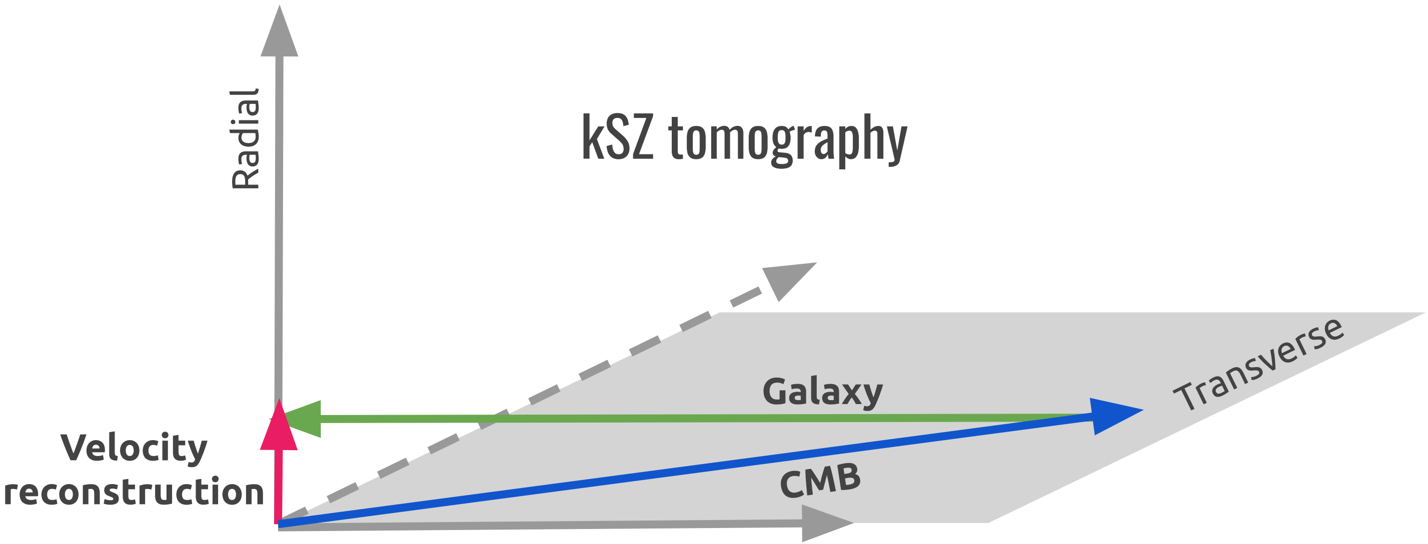
Bonus slides

CMB lensing



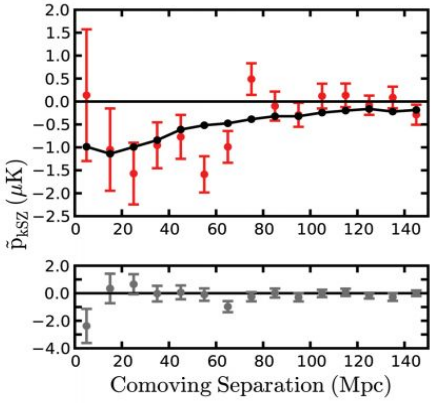
$$\hat{\phi}(L) = \langle TT \rangle_{\ell}$$

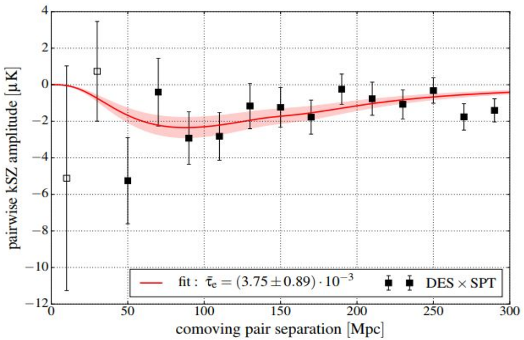
kSZ tomography

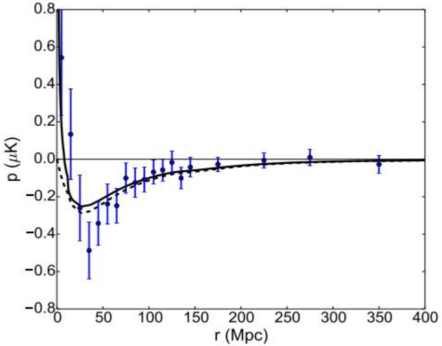


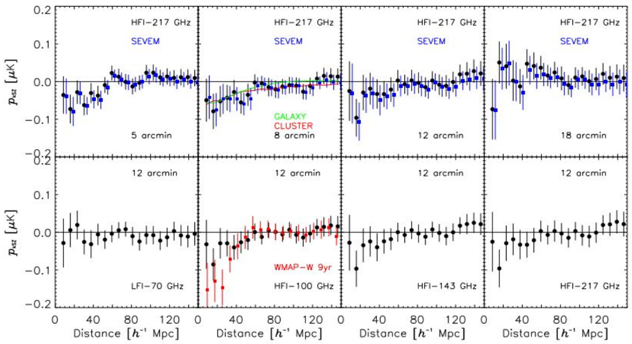
$$\langle v(k_L)\delta_g(k_S)T(\ell)\rangle$$

Bonus slide: pairwise kSZ detections









Step 2: cross-correlate velocity with galaxy pos.

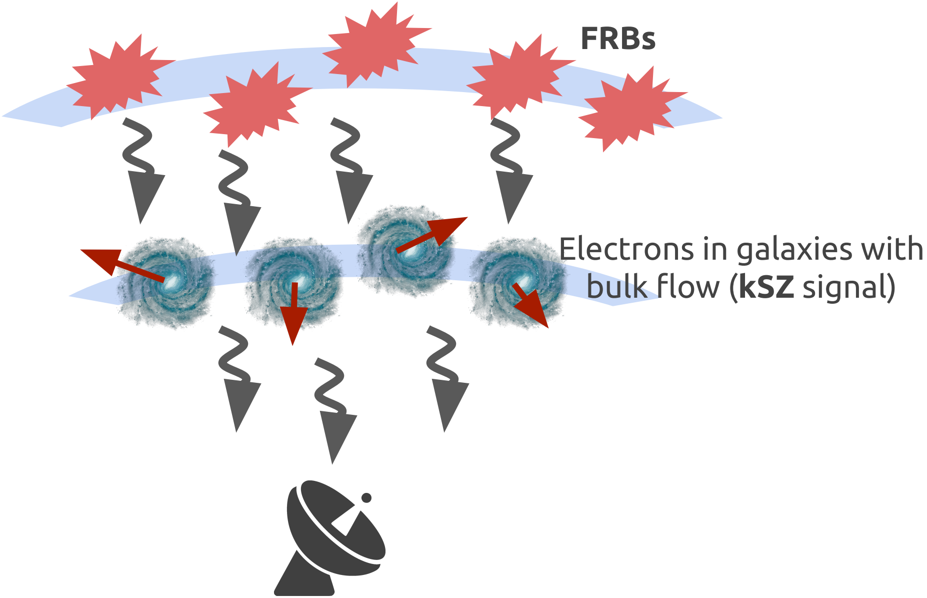
$$\langle \hat{v}\delta_g \rangle = \langle \langle \delta_g T \rangle_{k_S} \delta_g \rangle \sim \langle \langle \delta_g (v\delta_e) \rangle_{k_S} \delta_g \rangle$$

$$\sim \underbrace{P_{gv}(k_L)}_{\text{Cosmology}} \underbrace{\int dk_S P_{ge}(k_S)}_{\text{Astrophysics}}$$

Cosmology

Astrophysics

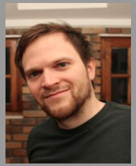
Scale-independent number


FRBs
Electrons in galaxies with bulk flow (**kSZ** signal)

New application: primordial non-Gaussianity (f_{NL})

Munchmeyer, MM++ 2018 arXiv:1810.13424

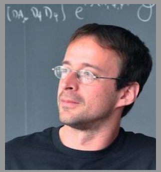
Moritz Munchmeyer

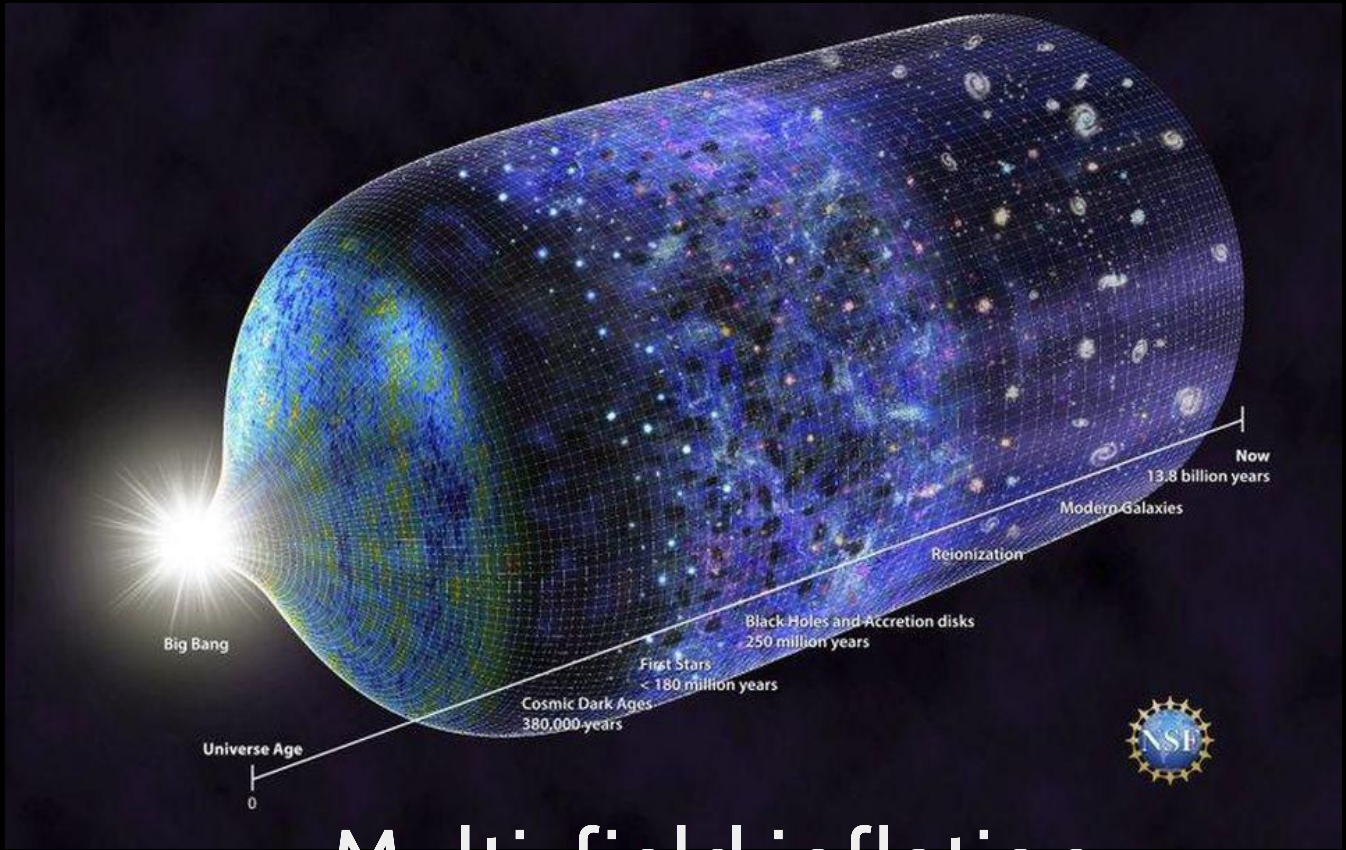


Simone Ferarro

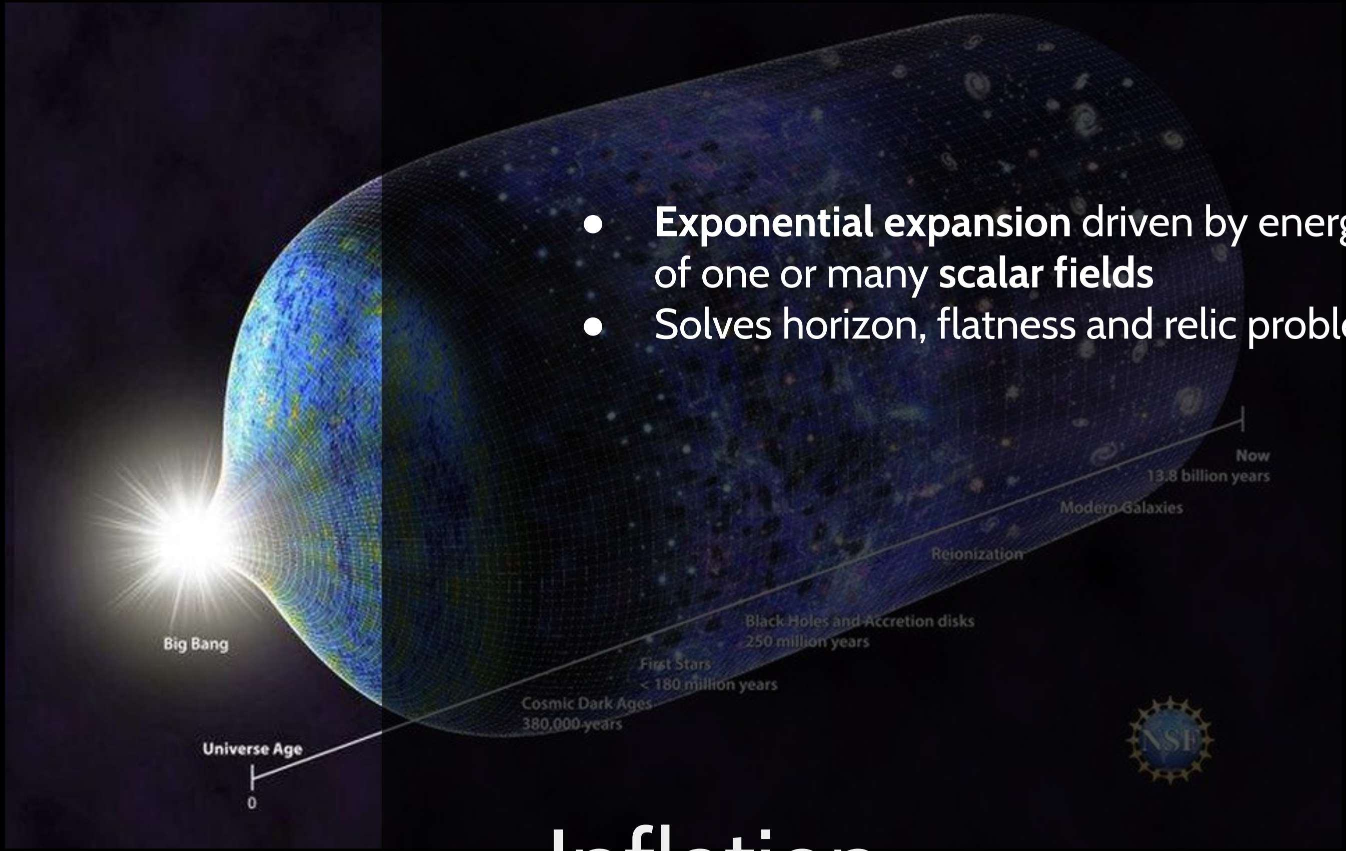
Matt Johnson

Kendrick Smith





Multi-field inflation

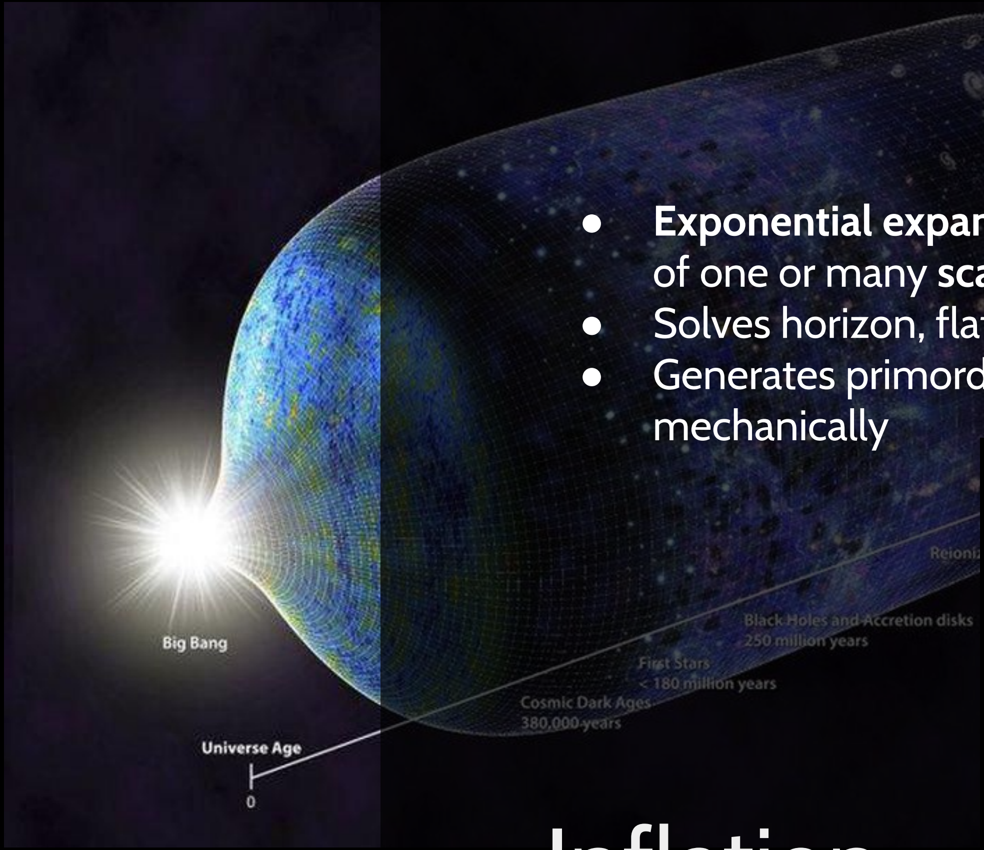


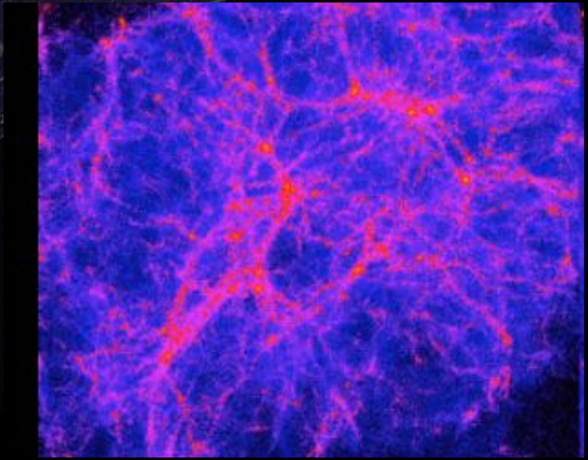
- **Exponential expansion** driven by energy density of one or many **scalar fields**
- Solves horizon, flatness and relic problems

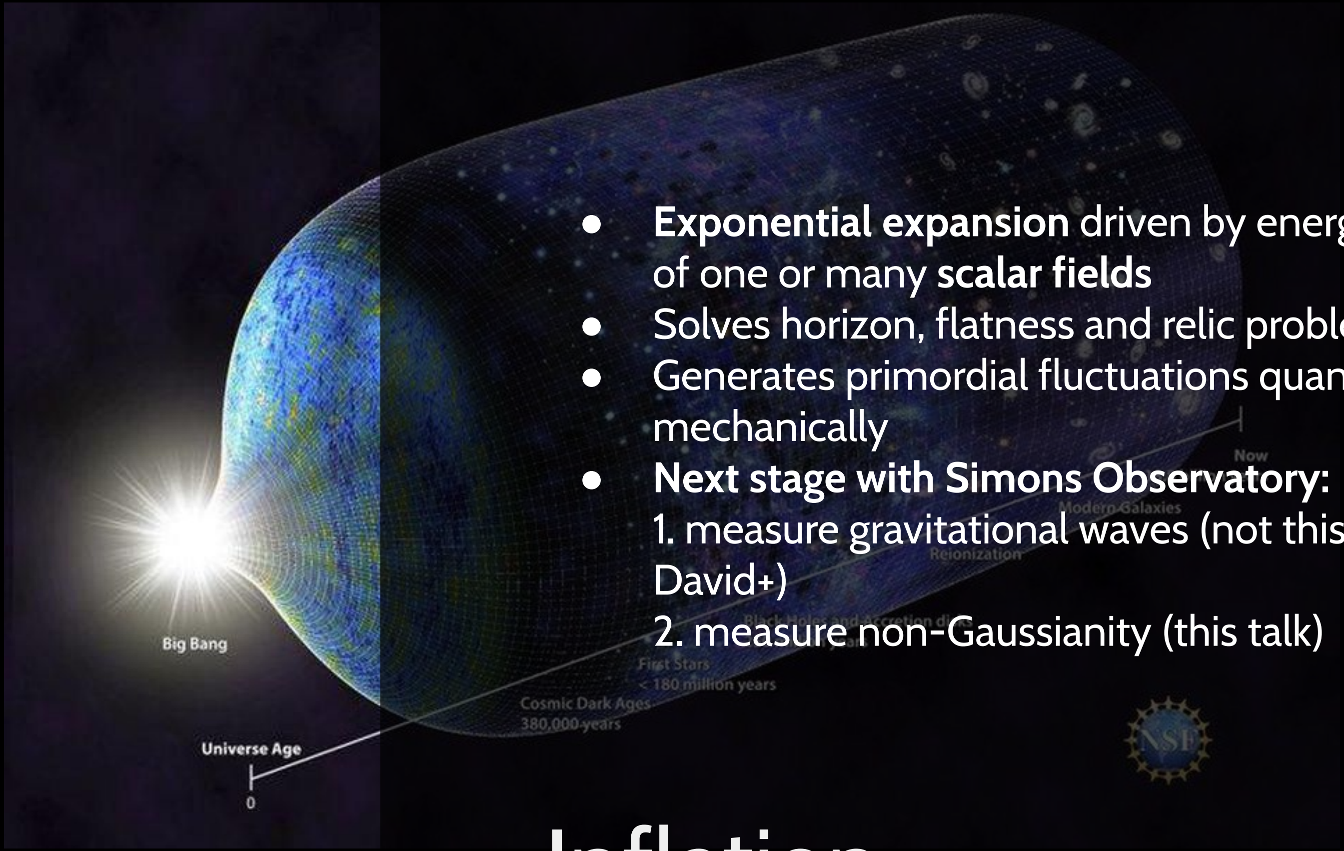
Inflation

Inflation

- **Exponential expansion** driven by energy density of one or many **scalar fields**
- Solves horizon, flatness and relic problems
- Generates primordial fluctuations quantum mechanically

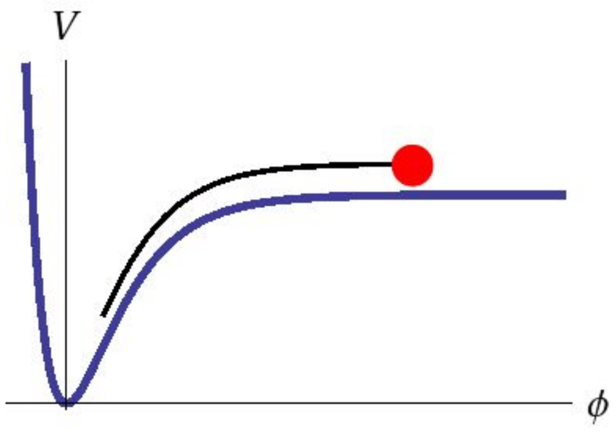


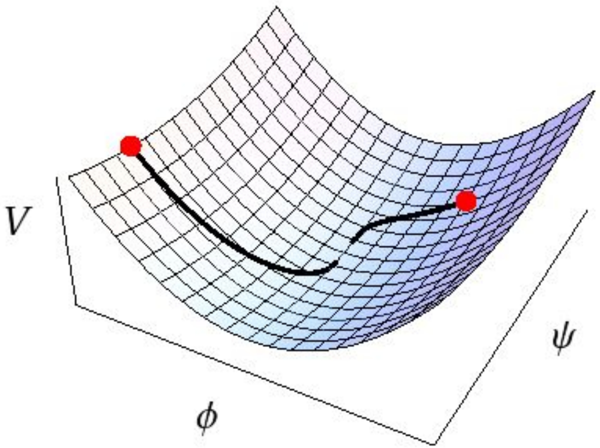




- **Exponential expansion** driven by energy density of one or many **scalar fields**
- Solves horizon, flatness and relic problems
- Generates primordial fluctuations quantum mechanically
- **Next stage with Simons Observatory:**
  1. measure gravitational waves (not this talk! Ask David+)
  2. measure non-Gaussianity (this talk)

Inflation



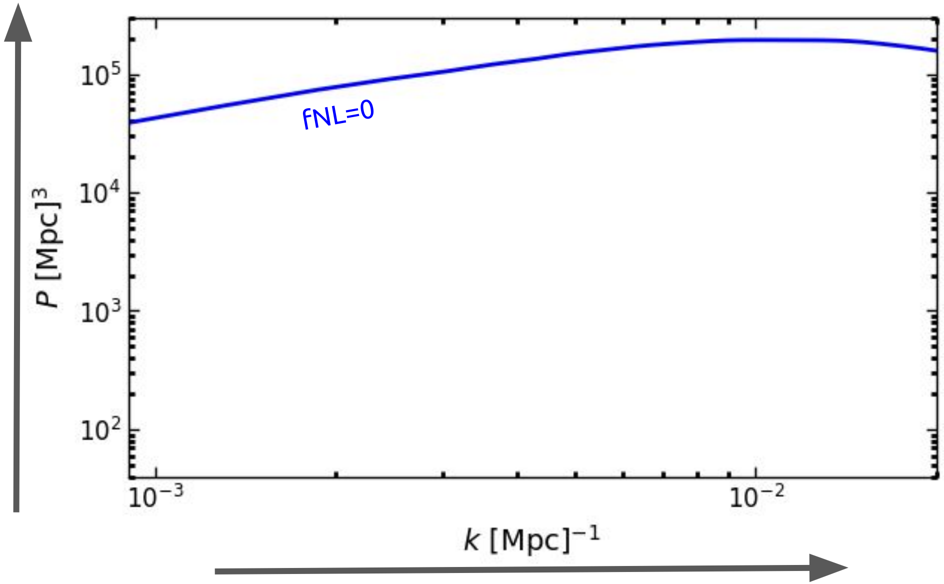


- Inflation driven by energy density of one or many **scalar fields**
- Current measurements (Planck CMB) consistent with single field
- Multiple fields naturally motivated by e.g. string theory
    - Predicts possibly detectable amounts of departure from Gaussianity
    - This shows up as **excess clustering of galaxies** on the largest scales *Dalal et al 2007*

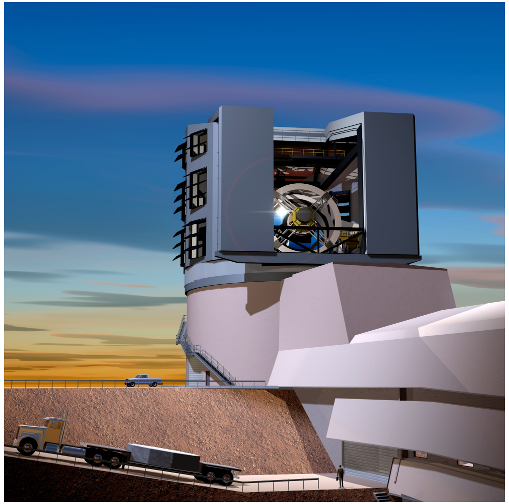
$$\Phi_{\rm NG} = \Phi_{\rm L} + f_{\rm NL}\Phi_{\rm L}^2$$

Galaxy surveys like Rubin/LSST measure clustering

Y-axis: How much clustering

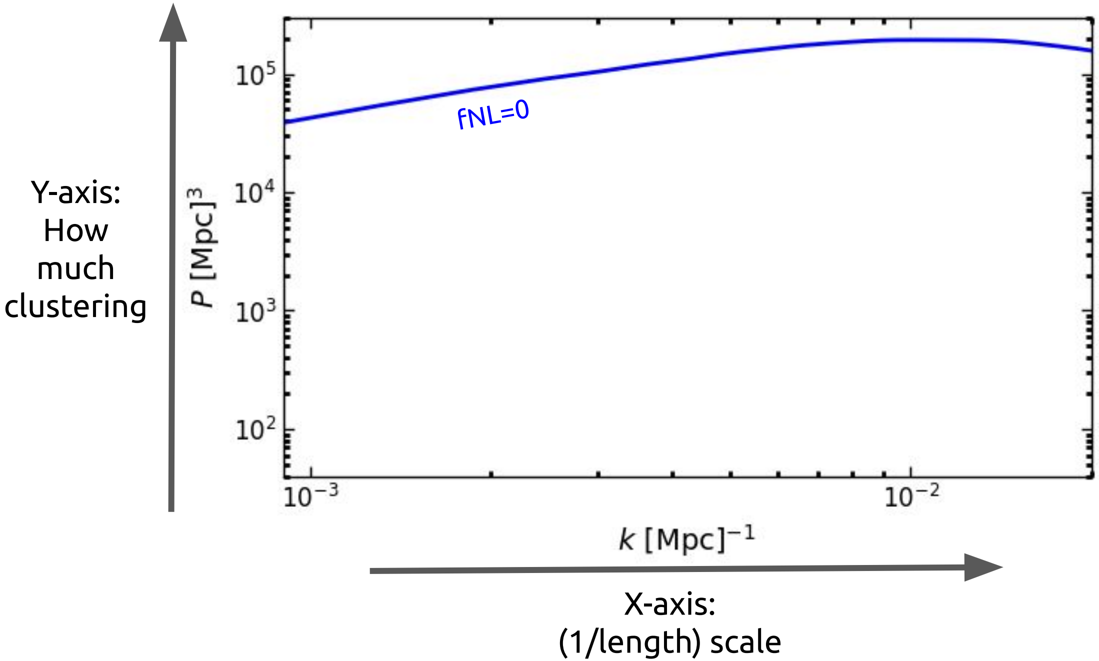


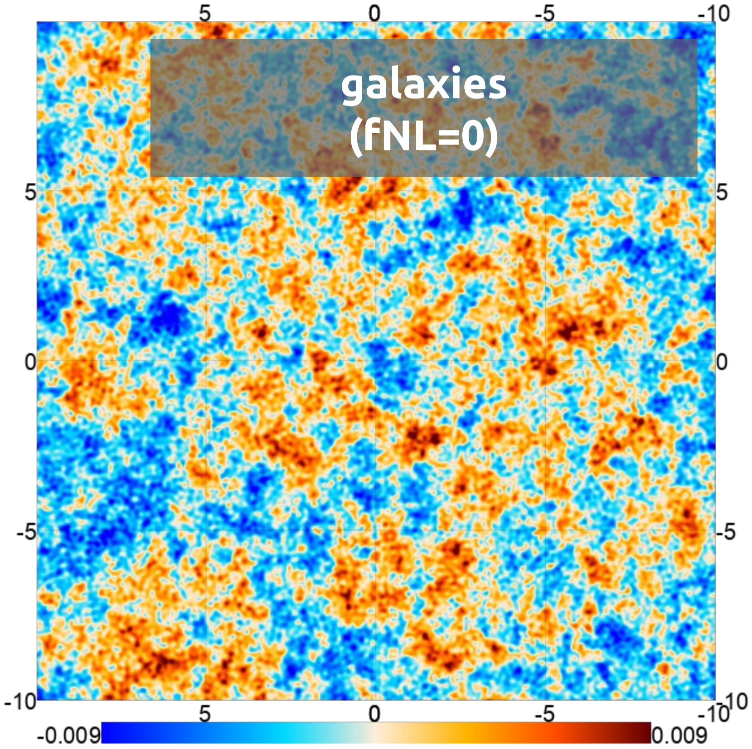
X-axis: (1/length) scale



Vera Rubin Observatory
LSST survey
Beginning in a couple of years
Several billion galaxies
Galaxies cluster with dark matter

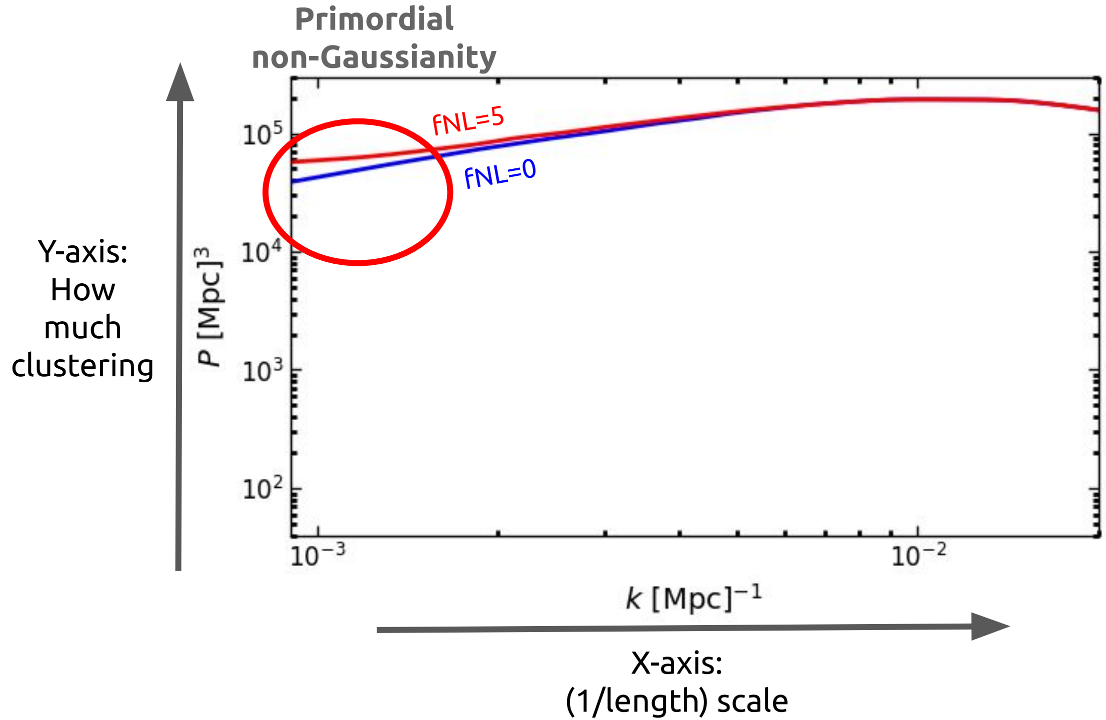
Galaxy surveys like Rubin/LSST measure clustering

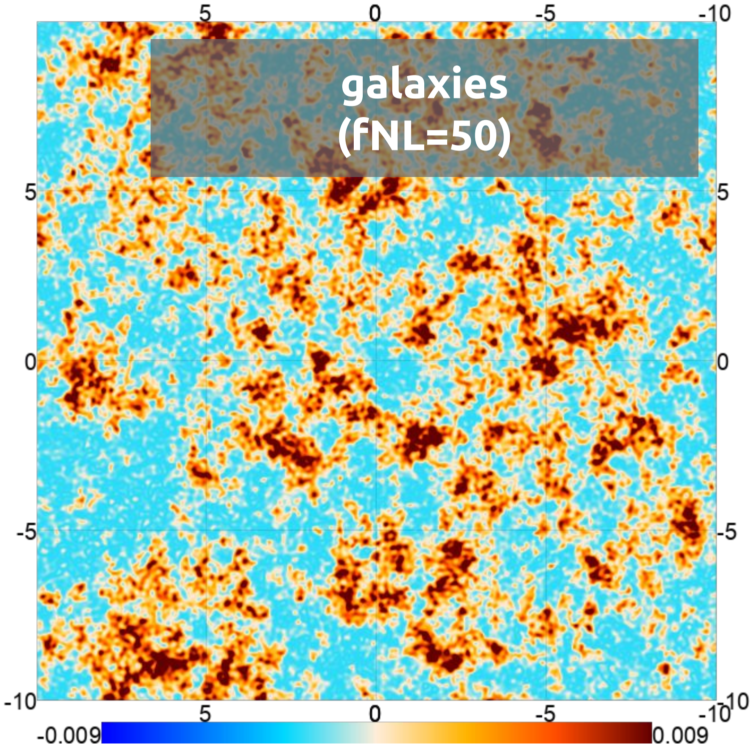




Mathew Madhavacheril, Perimeter Institute

Multi-field inflation predicts excess clustering **b(k)**





Mathew Madhavacheril, Perimeter Institute

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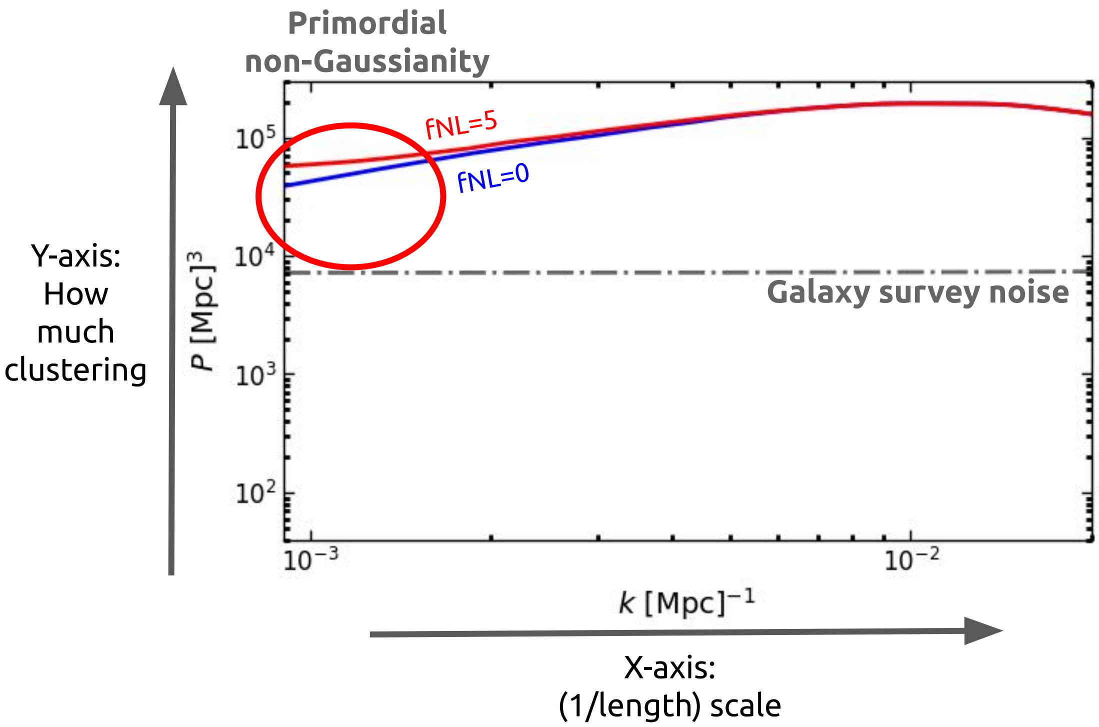


$$\Phi_{NG} = \Phi_L + f_{NL}\Phi_L^2$$

- Current constraint from Planck CMB sigma(fNL) ~ 5

  Sample variance limited

- Rubin/LSST sigma(fNL) ~ 2

  Sample variance limited

- MFI generically predicts fNL ~ 1

Can we improve large-scale clustering measurements beyond what galaxy surveys can measure?

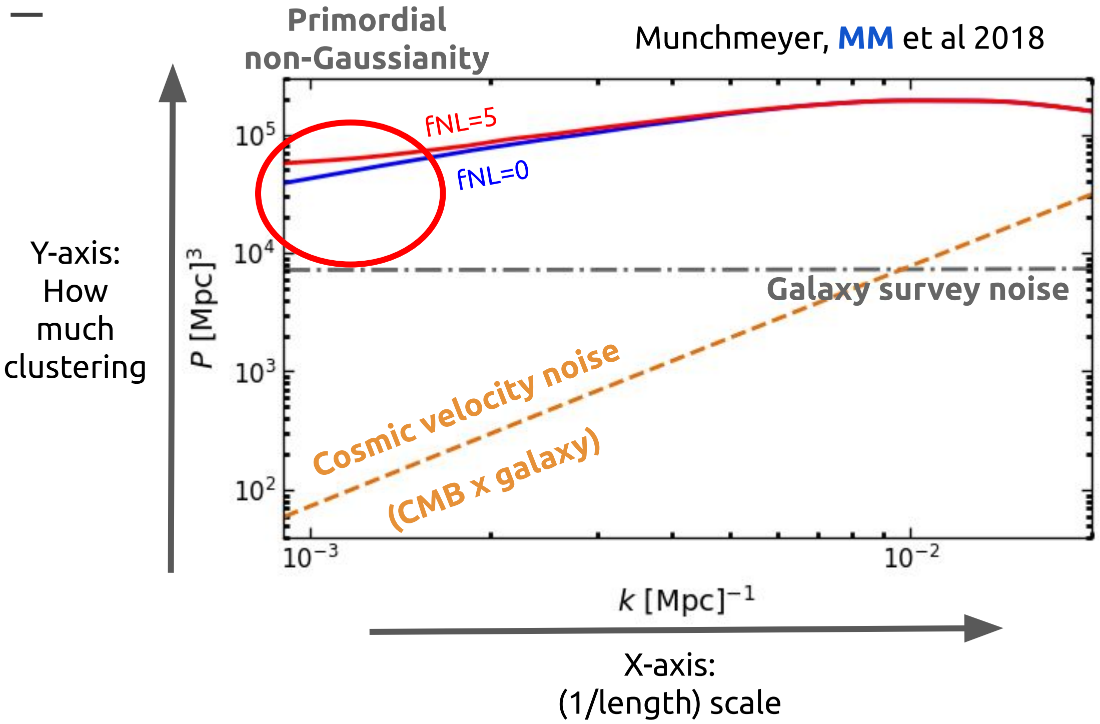
Can we improve large-scale clustering measurements beyond what galaxy surveys can measure?

Yes, by a lot!

New idea: reconstruct large scale velocity field using CMB imprint of moving clouds of electrons

Munchmeyer, **MM** et al, PRD 2018

Clustering of galaxies is scale-dependent on large scales in certain multi-field models of inflation, parameterized by f_{NL}



$$\delta_g = b_g \delta_m$$

$$v = \frac{b_v f a H}{k} \delta_m$$

Idea: ratio of (kSZ-)velocities and galaxies contains no matter field

$$v = \frac{b_v f a H}{k} \delta_m$$

With some reconstruction noise

$$\delta_g = b_g(f_{\rm NL}, k)\delta_m$$

With some shot noise

- Sample variance cancelled! Can measure bias without sample variance.
- Arbitrary improvement with CMB and galaxy survey noise improvement.
- Effectively done by measuring all auto and cross-correlations: Pgg, Pgv, Pvv
- Not affected by scale-independent astrophysics (tau) marginalization!

3x improvement in fNL from CMB-S4 kSZ + LSST

Galaxy clustering (LSST)	Galaxy clustering + kSZ velocities	
Pgg	Pgg, Pgv, Pvv	
$\sigma(f_{\rm NL})$ = 1.5	$\sigma(f_{\rm NL})$ = 1.0	Simons Observatory
	$\sigma(f_{\rm NL})$ = 0.5	CMB-S4

Larger improvement than similar method from CMB lensing (Schmittful, Seljak 2016) due to better correlation of velocities and galaxies